ABSTRACT

Mankind is facing the problem due to earthquake hazard since prehistoric times. Many of the developed and developing countries are under constant threats from earthquakes hazards. Theories of plate tectonics and engineering seismology have helped to understand earthquakes and also to predicate earthquake hazards on a regional scale. However, the regional scale hazard mapping in terms of seismic zonation has been not fully implemented in many of the developing countries like India. Agglomerations of large population in the Indian cities and poor constructions have raised the risk due to various possible seismic hazards. First and foremost step towards hazard reduction is estimation of the seismic hazards in regional scale. Objective of this study is to estimate the seismic hazard parameters for Lucknow, a part of Indo-Gangetic Basin (IGB) and develop regional scale microzonation map.

Lucknow is a highly populated city which is located close to the active seismic belt of Himalaya. This belt came into existence during the Cenozoic era (40-50 million years ago) and is a constant source of seismic threats. Many of the devastating earthquakes which have happened since prehistoric times such as 1255 Nepal, 1555 Srinagar, 1737 Kolkata, 1803 Nepal, 1833 Kathmandu, 1897 Shillong, 1905 Kangra, 1934 Bihar-Nepal, 1950 Assam and 2005 Kashmir. Historic evidences show that many of these earthquakes had caused fatalities even up to 0.1 million. At present, in the light of building up strains and non-occurrence of a great event in between 1905 Kangra earthquake and 1934 Bihar-Nepal earthquake regions the stretch has been highlighted as central seismic gap. This location may have high potential of great earthquakes in the near future. Geodetic studies in these locations indicate a possible slip of 9.5 m which may cause an event of magnitude 8.7 on Richter scale in the central seismic gap.

Lucknow, the capital of Uttar Pradesh has a population of 2.8 million as per Census 2011. It lies in ZONE III as per IS1893: 2002 and can be called as moderate seismic region. However, the city falls within 350 km radial distance from Main Boundary Thrust (MBT) and active regional seismic source of the Lucknow-Faizabad fault. Considering the ongoing seismicity of Himalayan region and the Lucknow-Faizabad fault, this city is under high seismic threat. Hence a comprehensive study of understanding the earthquake hazards on a regional scale for the Lucknow is needed.

In this work the seismic microzonation of Lucknow has been attempted. The whole thesis is divided into 11 chapters. A detailed discussion on the importance of this study, seismicity of Lucknow, and methodology adopted for detailed seismic hazard assessment and microzonation are presented in first three chapters. Development of region specific Ground Motion Prediction Equation (GMPE) and seismic hazard estimation at bedrock level using highly ranked GMPEs are presented in Chapters 4 and 5 respectively. Subsurface lithology, measurement of dynamic soil properties and correlations are essential to assess region specific site effects and liquefaction potential. Discussion on the experimental studies, subsurface profiling using geotechnical and geophysical tests results and correlation between shear wave velocity (SWV) and standard penetration test (SPT) N values are presented in Chapter 6. Detailed shear wave velocity profiling with seismic site classification and ground response parameters considering multiple ground motion data are discussed in Chapters 7 and 8. Chapters 9 and 10 present the assessment of liquefaction potential and determination of hazard index with microzonation maps respectively. Conclusions derived from each chapter are presented in Chapter 11. A brief summary of the work is presented below:

Attenuation relations or GMPEs are important component of any seismic hazard analysis which controls accurate prediction of the hazard values. Even though the Himalayas have experienced great earthquakes since ancient times, suitable GMPEs which are applicable for a wide range of distance and magnitude are limited. Most of the available regional GMPEs were developed considering limited recorded data and/or pure synthetic ground motion data. This chapter presents development of a regional GMPE considering both the recorded as well as synthetic ground motions. In total 14 earthquakes consisting of 10 events with recorded data and 4 historic events with Isoseismal maps are used for the same. Synthetic ground motions based on finite fault model have been generated at unavailable locations for recorded events and complete range distances for historic earthquakes. Model parameters for synthetic ground motion were arrived by detailed parametric study and from literatures. A concept of Apparent Stations (AS) has been used to generate synthetic ground motion in a wide range of distance as well as direction around the epicenter. Synthetic ground motion data is validated by comparing with available recorded data and peak ground acceleration (PGA) from Isoseismal maps. A new GMPE has been developed based on two step stratified regression procedure considering the combined dataset of recorded and synthetic ground motions. The new GMPE is validated by comparing with three recently recorded earthquakes events. GMPE proposed in this study is capable of predicting PGA values close to recorded data and spectral acceleration up to period of 2 seconds. Comparison of new GMPE with the recorded data of recent earthquakes shows a good matching of ground motion as well as response spectra. The new GMPE is applicable for wide range of earthquake magnitudes from 5 to 9 on Mw scale.

Reduction of future earthquake hazard is possible if hazard values are predicted precisely. A detailed seismic hazard analysis is carried out in this study considering deterministic and probabilistic approaches. New seismotectonic map has been generated for Lucknow considering a radial distance of 350 km around the city centre, which also covers active Himalayan plate boundaries. Past earthquakes within the seismotectonic region have been collected from United State Geological Survey (USGS), Northern California Earthquake Data Centre (NCEDC), Indian Meteorological Department (IMD), Seismic Atlas of India and its Environs (SEISAT) etc. A total of 1831 events with all the magnitude range were obtained. Collected events were homogenized, declustered and filtered for Mw $\geq$ 4 events. A total of 496 events were found within the seismic study region. Well delineated seismic sources are compiled from SEISAT. Superimposing the earthquake catalogue on the source map, a seismotectonic map of Lucknow was generated. A total of 47 faults which have experienced earthquake magnitude of 4 and above are found which are used for seismic hazard analysis. Based on the distribution of earthquake events on the seismotectonic map, two regions have been identified. Region I which shows high density of seismic events in the area in and around of Main Boundary Thrust (MBT) and Region II which consists of area surrounding Lucknow with sparse distribution of earthquake events. Data completeness analysis and estimation of seismic parameter “a” and “b” are carried out separately for both the regions. Based on the analysis, available earthquake data is complete for a period of 80 years in both the regions. Using the complete data set, the regional recurrence relations have been developed. It shows a “b” value of 0.86 for region I and 0.9 for Region II which are found comparable with earlier studies. Maximum possible earthquake magnitude in each source has been estimated using observed magnitude and doubly truncated Gutenberg-Richter relation. The study area of Lucknow is divided into 0.015^{o} x 0.015^{o} grid size and PGA at each grid has been estimated by considering all sources and the three GMPEs. A Matlab code was generated for seismic hazard analysis and maximum PGA value at each grid point was determined and mapped. Deterministic seismic hazard analysis (DSHA) shows that maximum expected PGA values at bedrock level varies from 0.05g in the eastern part to 0.13g in the northern region. Response spectrum at city centre is also developed up to a period of 2 seconds.

Further, Probabilistic seismic hazard analysis (PSHA) has been carried out and PGA values for 10 % and 2 % probability of exceedence in 50 years have been estimated and mapped. PSHA for 10 % probability shows PGA variation from 0.035g in the eastern parts to 0.07g in the western and northern parts of Lucknow. Similarly PSHA for 2 % probability of exceedence indicates PGA variation from 0.07g in the eastern parts while the northern parts are expecting PGA of 0.13g. Uniform hazard spectra are also developed for 2 % and 10 % probability for a period of up to 2 seconds. The seismic hazard analyses in this study show that the northern and western parts of Lucknow are more vulnerable when compared to other part.

Bedrock hazard values completely change due to subsoil properties when it reaches the surface. A detailed geophysical and geotechnical investigation has been carried out for subsoil profiling and seismic site classification. The study area has been divided into grids of 2 km x 2 km and roughly one geophysical test using MASW (Multichannel Analysis Surface Wave) has been carried out in each grid and the shear wave velocity (SWV) profiles of subsoil layers are obtained. A total of 47 MASW tests have been carried out and which are uniformly distributed in Lucknow. In addition, 12 boreholes have also been drilled with necessary sampling and measurement of N- SPT values at 1.5 m interval till a depth of 30 m. Further, 11 more borelog reports are collected from the same agency hired for drilling the boreholes. Necessary laboratory tests are conducted on disturbed and undisturbed soil samples for soil classification and density measurement. Based on the subsoil informations obtained from these boreholes, two cross-sections up to a depth of 30 m have been generated. These cross-sections show the presence of silty sand in the top 10 m at most of the locations followed by clayey sand of low to medium compressibility till a depth of 30 m. In between the sand and clay traces of silt were also been found in many locations. In addition to these boreholes, 20 deeper boreholes (depth ≥150 m) are collected from Jal Nigam (Water Corporation) Lucknow, Government of Uttar Pradesh. Typical cross-section along the alignment of these deeper boreholes has been generated up to 150 m depth. This cross-section shows the presence of fine sand near Gomati while other locations are occupied by surface clayey sand. Also, the medium sand has been found in the western part of the city at a depth of 110 m which continues till 150 m depth. On careful examination of MASW and boreholes with N-SPT, 17 locations are found very close and SWV and N-SPT values are available up to 30 m depth. These SWV and N-SPT values are complied and used to develop correlations between SWV and N-SPT for sandy soil, clayey soil and all soil types. This correlation is the first correlation for IGB soil deposits considered measured data up to 30 m. The new correlation is verified graphically using normal consistency ratio and standard percentage error with respect to measured N-SPT and SWV. Further, SWV and N-SPT profiles are used to estimate 30 m average SWV and N values and to prepare site classification map as per National Earthquake Hazard Reduction Program (NEHRP) site classification scheme. N-SPT shows that the entire Lucknow belongs to site classes D and E. Similarly, the 30 m average SWV (V_s^{30}) values shows site class C and D.

Even though the size of earthquake is moderate, presence of soft soil near the surface can amplify the ground motion and can cause devastating damages. This chapter presents estimation of ground response parameters for the study area considering multiple regional ground motions. The response of ground during an event is a function of frequency, amplitude and duration of base/bedrock motion. Based on seismic hazard analysis bedrock PGA values, multiple ground motion is selected as input ground motion.

The entire PGA variation was divided into 4 classes and total of 18 bedrock motions are used as input ground motions for response study. Ground motions have been selected such way that variation of frequency, duration and amplitude can be covered in the prediction of site response parameters. These motions were recorded during different earthquakes along the Himalayan belt. The deeper borehole reports at Lucknow showed absence of bedrock up to depth of 150 m. Hence input ground motions are given at dense layer having shear wave velocity 760±60 m/s rather at 30 m. Out of 47 SWV profiles only 29 profiles are having very dense layer, which are used for site response analysis. Nonlinear site response model DEEPSOIL V 3.7 has been used in the study. Standard modulus gradation and damping curves were selected based for types of soil layers found in the borehole. The depth of water table and density to estimate shear modulus for each soil column was taken from the nearest borehole. Each soil column was subjected to 18 ground motions and the response of the soil column in terms of peak spectral acceleration, amplification factor, predominant frequency has been estimated. Site response results from each borehole for 18 input motions are used to estimate maximum and average amplification values at respective borehole location. Two maps showing the average and maximum amplification factors are prepared. These maps show that the amplification factor varying from 2 to 6 with lesser values in the central and southern parts of Lucknow while higher values were obtained from the northern and western parts. Surface PGA values are estimated considering PGA from hazard analysis and average and maximum amplification factors. Surface PGA maps based on amplification factors show PGA variation from 0.12 g in the southern and eastern parts to 0.72 g in the northern and western parts of Lucknow. Typical peak spectral acceleration, period corresponding to peck spectral acceleration and predominant frequencies are arrived from response and Fourier spectrum and mapped for the study area.

Another important earthquake induced hazard is liquefaction. Even though many historic earthquakes caused liquefaction in India, very limited attempt has been made to map liquefaction potential in IGB. In this study, a detailed liquefaction analysis has been carried out for Lucknow a part of Ganga Basin to map liquefaction potential. Initially susceptibility of liquefaction for soil deposits has been assessed by comparing the grain size distribution curve obtained from laboratory tests with the range of grain size distribution for potentially liquefiable soils. Most of surface soil deposits in the study area are susceptible to liquefaction. At all the 23 borehole locations, measured N-SPT values are corrected for (a) Overburden Pressure (C_N), (b) Hammer energy (C_E), (c) Borehole diameter (C_B), (d) presence or absence of liner (C_S), (e) Rod length (C_R) and (f) fines content (C_{fines}). Surface PGA values at each borehole locations are used to estimate Cyclic Stress Ratio (CSR). Corrected N-SPT values [$(N_1)_{60CS}$] are used to estimate Cyclic Resistance Ratio (CRR) at each layer. CSR and CRR values are used to estimate Factor of Safety (FOS) against liquefaction in each layer. Least factor safety values are indentified from each location and presented liquefaction factor of safety map for average and maximum amplified PGA values. These maps highlight that northern, western and central parts of Lucknow are very critical to critical against liquefaction while southern parts shows moderate to low critical area. The entire alignment of river Gomati falls in very critical to critical regions for liquefaction. Least FOS shows worst scenario and does not account thickness of liquefiable soil layers. Further, these FOS values are used to determine Liquefaction Potential Index (LPI) of each site and developed LPI map. Based on LPI map, the Gomati is found as high to very high liquefaction potential region. Southern and the central parts of Lucknow show low to moderate liquefaction potential while the northern and western Lucknow has moderate to high liquefaction potential.

All possible seismic hazards maps for Lucknow have been combined to develop final microzonation map in terms of hazard index values. Hazard index maps are prepared by combining rock PGA map, site classification map in terms of shear wave velocity, amplification factor map, and FOS map and predominant period map by adopting Analytical Hierarchy Process (AHP). All these parameters have been given here in the order starting with maximum weight of 6 for PGA to lower weight of 1 for predominant frequency. Normalized weights of each parameter have been estimated. Depending upon the variation of each hazard parameter values, three to five ranks are assigned and the normalized ranks are calculated. Final hazard index values have been estimated by multiplying normalized ranks of each parameter with the normalized weights. Microzonation map has been generated by mapping hazard index values. Three maps were generated based on DSHA, PSHA for 2%

and 10 % probability of exceedence in 50 years. Hazard index maps from DSHA and PSHA for 2 % probability show similar pattern. Higher hazard index were obtained in northern and western parts of Lucknow and lower values in others. The new microzonation maps can help in dividing the Lucknow into three parts as high area i.e. North western part, moderate hazard area i.e. central part and low hazard area which covers southern and eastern parts of Lucknow. This microzonation is different from the current seismic code where all area is lumped in one zone without detailed assessment of different earthquake hazard parameters.

Finally this study brings out first region specific GMPE considering recorded and synthetic ground monitions for wide range of magnitudes and distances. Proposed GMPE can also be used in other part of the Himalayan region as it matches well with the highly ranked GMPEs. Detailed rock level PGA map has been generated for Lucknow considering DSHA and PSHA. A detailed geotechnical and geophysical experiments are carried out in Lucknow. These results are used to develop correction between SWV and N-SPT values for soil deposit in IGB and site classification maps for the study area. Amplification and liquefaction potential of Lucknow are estimated by considering multiple ground motions data to account different earthquake ground motion amplitude, duration and frequency, which is unique in the seismic microzonation study.